Modeling the broadband persistent emission of magnetars ⋆

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Abstract

In this paper, we discuss our first attempts to model the broadband persistent emission of magnetars within a self consistent, physical scenario. We present the predictions of a synthetic model that we calculated with a new Monte Carlo 3-D radiative code. The basic idea is that soft thermal photons (e.g. emitted by the star surface) can experience resonant cyclotron upscattering by a population of relativistic electrons threated in the twisted magnetosphere. Our code is specifically tailored to work in the ultra-magnetized regime; polarization and QED effects are consistently accounted for, as well different configurations for the magnetosphere. We discuss the predicted spectral properties in the $0.1 - 1000$ keV range, the polarization properties, and we present the model application to a sample of magnetars soft X-ray spectra.

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1 Introduction

Soft gamma-ray repeaters (SGRs) and anomalous X-ray pulsars (AXPs) are peculiar X-ray sources which are believed to be magnetars: ultra-magnetized neutron stars with surface field in excess of 10^{14} G, i.e. well above the QED threshold (see Mereghetti, 2008, for a recent review). In this scenario, the ultra-strong field is responsible for powering the X-ray emission of the source which otherwise is too high to be explained in terms of spin down losses. Spectral analysis is an important tool in magnetar astrophysics since it can provide key information on the emission mechanisms. The persistent (i.e. outside bursts) soft X-ray (< 10 keV) spectra of magnetars is typically reproduced by a double component model, consisting of a blackbody (BB, with $kT \sim 0.3 - 0.6$ keV) plus a power-law (PL, with photon index $\Gamma \sim 2 - 4$). Moreover, *INTEGRAL* observations have shown that, while in quiescence, magnetars emit substantial persistent radiation also at higher energies, up to a few hundreds of keV. The X-ray persistent emission above 20 keV has a power-law spectral shape ($\Gamma_h \sim 2$) which, in particular in AXPs, is markedly harder than that observed below 10 keV (see again Mereghetti, 2008, and references therein). Despite these phenomenological fitting models have been applied for many years, a physical interpretation of the various spectral components is still missing.

It has been proposed by several authors (Duncan & Thompson, 1992; Thompson & Duncan, 1993; Thompson, Lyutikov & Kulkarni, 2002) that, at variance with standard radio-pulsars, in magnetars the magnetosphere can be twisted. This, in turn, has a number of observational consequences. Twisted magnetic fields are permeated by currents with substantial density, much in excess of the Goldreich-Julian current which is expected in a potential field. Magnetospheric charges can efficiently interact with the primary radiation from the neutron star and/or with the magnetic field itself, giving rise to different emission processes. In particular, it has been widely suggested that the BB+PL spectral shape that is observed below ~ 10 keV may be accounted for if the soft, thermal spectrum emitted by the star surface is distorted by resonant cyclotron scattering (RCS) onto the magnetospheric charges. Since electrons permeate a spatially extended region of the magnetosphere, where the magnetic field varies by order of magnitudes, resonant scattering is not expected to manifest itself as a series of narrow spectral lines (corresponding to the successive harmonics), but instead to lead to the formation of a hard tail superimposed to the seed thermal bump.

2 Building spectral models

Recently, several efforts have been carried out in order to test the resonant cyclotron scattering model quantitatively against real data in the soft X-ray range, using different approaches and with a varying degree of sophistication. The first, seminal attempts have been presented by Lyutikov & Gavriil (2006). These authors studied a simplified, 1-D model by assuming that seed photons are emitted by the NS surface radially and with a blackbody spectrum, and magnetic Thomson scattering occurs in a thin, plane parallel magnetospheric slab permeated by a static, non-relativistic, warm medium at constant electron density. They neglect all effects of electron recoil, as those related to the currents bulk motion. Despite the simplification, this model has the main advantage to be semi-analytical and, when systematically applied to X-ray data, has been proved to be successful in catching the gross characteristics of the observed soft X-ray spectrum (Rea et al., 2007a,b, 2008). The same model has been extended by Güver, et al. (2007) who relaxed the BB approximation for the surface radiation and included atmospheric effects. More recently, 3-D Monte Carlo calculations have been presented by Fernandez & Thompson (2007), although these spectra have never been applied to fit X-ray observations. In this paper, we present the predicted spectra obtained via a new 3-D Monte Carlo simulation (see Nobili, Turolla & Zane, 2008a,b, for details). Polarization and, for the first time, QED effects are consistently accounted for, as well different configurations for the magnetosphere. We will discuss the predicted spectral properties in the in the $0.1 - 1000$ keV range, the polarization properties and we will present the model application to a sample of magnetars spectra in the soft X-ray range.

3 A Monte Carlo Model

We decided to use a Monte Carlo approach since this technique is particularly suitable for the problem at hand for several reasons. For instance, it allows us to follow individually a large sample of photons, treating probabilistically their interactions with charged particles; it can handle very general (3-D) geometries; is quite easy to code, and relatively fast; and is ideal for purely scattering media. In order to perform such kind of simulations, we need to specify three basic ingredients: a) the space and energy distribution of seed photons, b) the same for the magnetospheric electrons (the "scatterers") and c) a prescription for the cross section. Although our code is completely general, and can handle different thermal maps, different models of surface emission and magnetic configurations, the models presented in this draft are all computed by assuming that the whole surface emits isotropically as a BB at a single temperature, kT, and that the magnetic field is a force-free, self-

similar, twisted dipole characterized by the value of the twist angle, $\Delta\Phi$ and of the polar magnetic field B (Thompson, Lyutikov & Kulkarni, 2002). In absence of a self-consistent treatment of the electrodynamics of the magnetosphere (see Nobili, 2009), the electron velocity distribution has been assumed a priori. Our model is based on a simplified treatment of the charge carriers velocity distribution which accounts for the particle collective motion, in addition to the thermal one. Electrons occupy a set of quantized Landau levels in the transverse plane, while their distribution parallel to the field is taken to be a 1-D relativistic Maxwellian at temperature T_e, superimposed to a bulk motion with velocity β_{bulk} (in units of the light velocity c). In turn, both T_e and β_{bulk} are treated as free model parameters. We then built two versions of the code. The first one is computationally faster, and scattering is treated in the magnetic Thomson limit, neglecting electron recoil along the field direction. This means that simulated spectra are only valid up to a few tens of keV ($h\nu < mc^2/\gamma$ keV, $B/B_{QED} < 10$). The second version of the code is computationally heavier, but it includes the relativistic QED resonant cross section (see Nobili, Turolla & Zane, 2008b, and references therein), which is required to extend spectral predictions in the hard X-rays band (i.e. up to and beyond the *INTEGRAL* energy range).

4 Predicted Spectral and polarization properties

4.1 Results computed in the Thomson limit

Figs. 1, 2 show a series of spectra computed in the Thomson limit, and illustrate the effects on the spectral shape of varying β_{bulk} and kT_e, respectively. As mentioned above, although the curves in these figures extend up to ~ 1000 keV, being these spectra computed in the non-relativistic limit they should only be considered valid up to a few tens of keV. Spectra are plotted for two values of the magnetic colatitude at infinity, Θ_s, one for each hemisphere (top and bottom panels). By comparing the left and right panel in each figure, we can immediately notice the absence of symmetry between the north and the south hemispheres: as Θ_s increases, spectra become more and more comptonized. This reflects the fact that in our model, which accounts for the charges bulk velocity, currents flow has a preferential direction (in this simulation from the north to the south pole along the field lines). As a consequence, an observer located in the northern hemisphere "sees" currents flowing away from him and observes spectra that are less comptonized with respect to an observer in the southern hemisphere (which "sees" currents flowing towards him). Of course the opposite choice for the current direction would simply result in $\Theta_s \rightarrow 180^\circ - \Theta_s$.

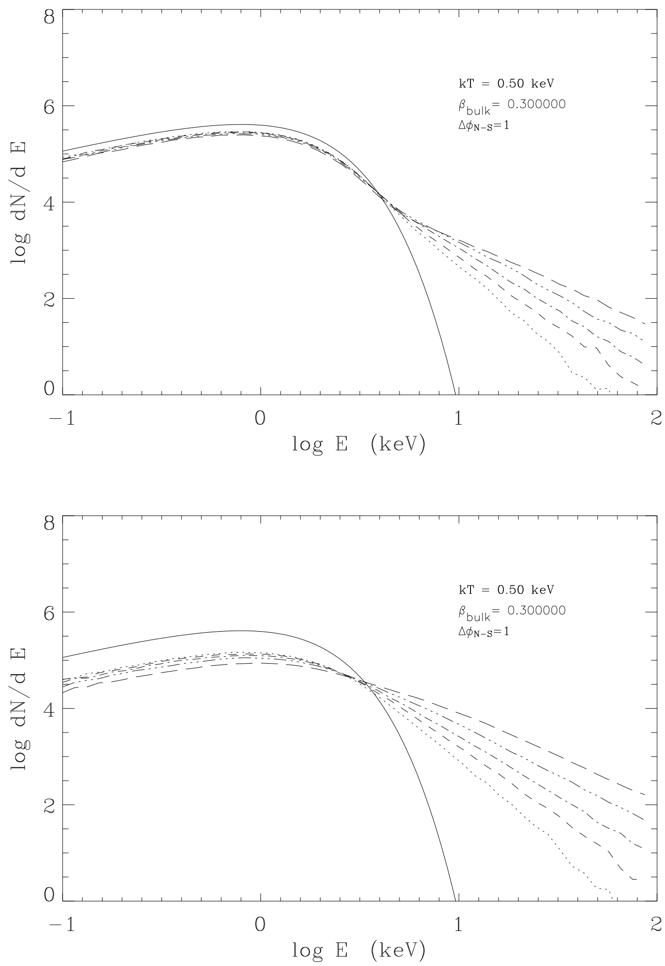

Fig. 1. Computed spectra for $B = 10^{14}$ G, $kT = 0.5$ keV, $\beta_{bulk} = 0.3$, $\Delta\phi = 1$ and different values of kT_e: 5 keV (dotted), 15 keV (short dashed), 30 keV (dash-dotted), 60 keV (dash-triple dotted) and 120 keV (long dashed). The solid line represents the seed blackbody. The two panels correspond to two different values of the magnetic colatitude of the observer: $\Theta_s = 64°$ (top) and $\Theta_s = 116°$ (bottom). Figure from Nobili, Turolla & Zane (2008a); see the original paper for all details.

As it can be seen from Figs. 1, 2, an increase in either β_{bulk} or kT_e always corresponds to an increase in the comptonization degree of the spectrum. The same is true for an increase in the twist angle, $\Delta\phi$, which translates in an increase in the electron number density. As shown in the bottom panel of Fig. 2, the effect is particularly notable in the case of β_{bulk}. If $\beta_{bulk} > 0.5$, an observer located in the southern hemisphere (i.e. with currents flowing towards him) sees a spectrum which is no more peaked at $\sim kT$, but peaks instead at about the thermal energy of the scattering particles. This is because under these conditions Comptonization starts to saturate and photons fills the Wien peak of the Bose-Einstein distribution. This is observationally important, since it means that in some cases the observed thermal bump may be unrelated to

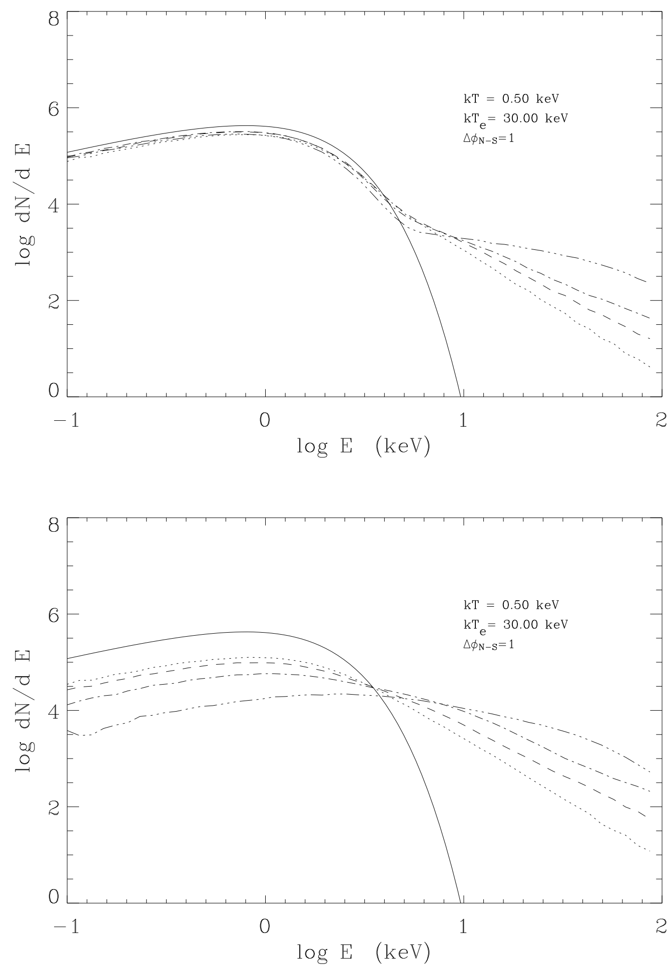

Fig. 2. Computed spectra for $B = 10^{14}$ G, $kT = 0.5$ keV, $kT_e = 30$ keV, $\Delta\phi = 1$ and different values of β_{bulk}: 0.3 (dotted), 0.5 (short dashed), 0.7 (dash-dotted) and 0.9 (dash-triple dotted). The solid line represents the seed blackbody. The two panels correspond to two different values of the magnetic colatitude of the observer: $\Theta_s = 64°$ (left) and $\Theta_s = 116°$ (right). Figure from Nobili, Turolla & Zane (2008a); see the original paper for all details.

the peak of the seed blackbody, but instead may give a direct information on the energy of the magnetospheric particles. Moreover, for intermediate values of the parameters, spectra can be double humped, with a downturn between the two humps.

4.2 Looking at magnetars with polaroid glasses

In Fig. 3 we show, as a function of β_{bulk}, the degree of polarization of the emerging radiation, defined as $|N_{extr} - N_{ord}|/(N_{extr} + N_{ord})$ where N_{extr} and N_{ord} are, respectively, the number of ordinary and extraordinary photons col-

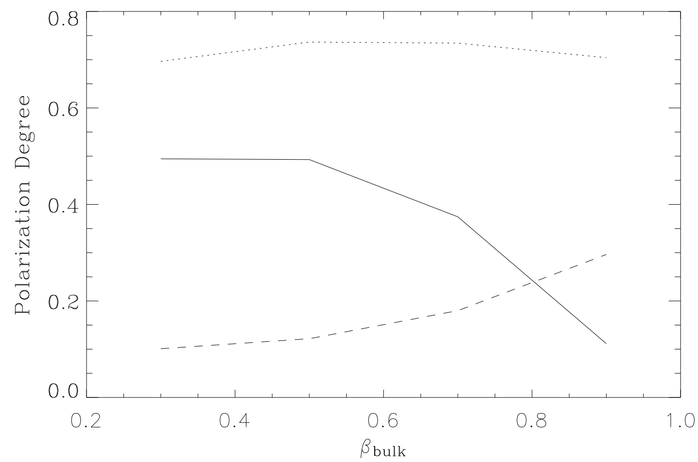

Fig. 3. Degree of polarization ($0.1 - 1000$ keV band) as a function of β_{bulk} for $kT_e = 30$ keV and $\Delta\phi = 1$, $B = 10^{14}$ G, $kT = 0.5$ keV, $\beta_{bulk} = 0.3$. Different curves correspond to: seed photons 100% polarized in the ordinary (solid line), extraordinary mode (dotted line), and unpolarized (dashed line). Figure from Nobili, Turolla & Zane (2008a); see the original paper for all details.

lected at infinity. The polarization degree is computed in the $0.1 - 1000$ keV band, it has been averaged over frequency, over the whole emitting surface and over the sky at infinity. As it can be seen, the efficiency at which completely polarized surface radiation is depolarized increases by increasing the strength of magnetospheric upscattering, i.e. by increasing β_{bulk}. We found similar results when increasing kT_e or $\Delta\phi$. The depolarization effect is stronger for ordinary seed photons, for which the probability of undergoing mode switching in the scattering process is higher. As the figure shows, would the surface radiation be completely unpolarized, while passing through the magnetosphere, it can acquire only a relatively small degree of linear polarization: typically 10-20%, up to 30% for very extreme values of the current bulk velocity. This means that, would future observations of X-ray polarization result in measurements larger than 10-30%, the excess has to be attributed to an intrinsic property of the surface radiation.

4.3 Relativistic, QED scattering

As previously mentioned, the treatment based on the Thomson limit becomes inadeguate when modelling the emission at higher energies, as that observed by *INTEGRAL* up to ~ 200 keV. Proper investigation of this range demands a complete QED treatment of magnetic Compton scattering. This is mandatory independently on the energy of the scatterers. If highly relativistic particles are considered, a photon can be boosted to quite large energies in a single scattering (making electron recoil important) and, if it propagates

towards the star, it may scatter again where the field is above the QED limit. Even in presence of mildly relativistic particles, in order to populate the hard tail it is necessary that soft photons experience multiple scatterings, during which the resonant condition is matched in regions characterized by a progressively higher field, again making QED effects non-negligible.

The Compton cross-section for electron scattering in the presence of a magnetic field was first studied in the non-relativistic limit by Canuto, Lodenquai & Ruderman (1971), and the QED expression was derived long ago by many authors (Herold, 1979; Daugherty & Harding, 1986; Bussard, Alexander & Mészáros, 1986; Harding & Daugherty, 1991). However, its form is so complicated to be often of little practical use in numerical calculations. On the other hand, since we are only interested in making spectral predictions for the continuum emission (and not on the details of the cyclotron lines profile), in our case we can safely assume that scattering occurs *at resonance*. We recently investigated this limit, and presented a complete, workable set of expressions for the QED cross section which can be used in our Monte Carlo simulations of photon scattering (Nobili, Turolla & Zane, 2008b). Our expressions are completely general in the sense that no limiting assumption is made on the magnetic field strength, and can be generalized to scattering onto positive charges (positrons). However, our present aim is to use them for spectral modelling in the $\sim$ 0.1-200 keV range, in which case resonant scattering of soft photons necessarily occurs where $B/B_{QED} < 1$. This allows us to restrict to the case in which Landau-Raman scattering occurs only up to the second Landau level, which makes the numerical computation faster. Photon spawning during the de-excitation is consistently accounted for. In order to verify the necessity of the QED computation, we compared our cross sections with the non-relativistic limit, and we found significant deviations even for $B/B_{QED} > 0.1$.

In Figs. 4,5 we show a few spectra computed by using our Monte Carlo code with the full QED scattering cross section (top panel), and their analogues computed by using the cross section in the Thomson limit (bottom). As we can see, below a few tens of keV the two spectra are identical, confirming the validity of the use of the Thomson limit when making predictions in the *XMM-Newton* range. On the other hand, if electrons are mildly relativistic (Fig. 4), when considering self-consistently electron recoil and QED effects the spectrum exhibits a break at higher energies. This is due to the fact that, if the Lorentz factor of electrons is $\gamma \sim$ a few, each scattering characterized by a limited energy gain. Therefore, in order to populate the hard energy tail soft seed photons need to experience a series of successive scatterings. On the other hand, the efficiency of the QED cross section decreases with increasing energy (or, being the process resonant, with increasing the magnetic field) and the combination of these two effects leads to the appearance of the spectral break. Unfortunately, this means that the energy of the break depends on a series of processes and on the details of the magnetic field configuration and its

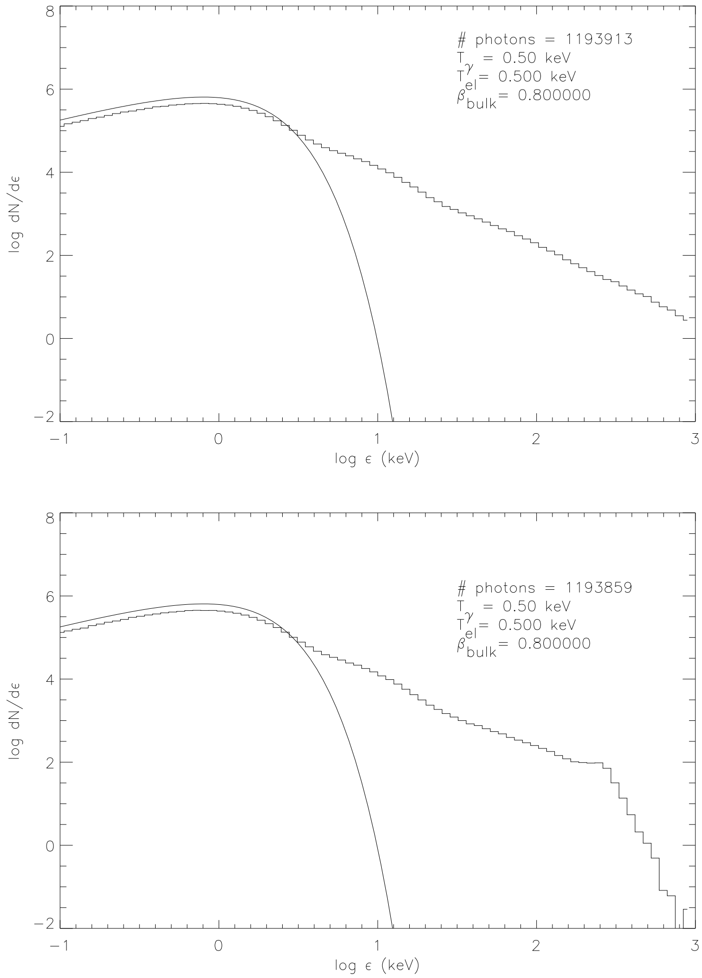

Fig. 4. Computed spectra for $B = 10^{14}$ G and $\Delta\phi = 1$. The top panel shows spectra computed by using the cross section in the Thomson limit, while on the bottom we use the full QED expression of resonant scattering. Here electrons are mildly relativistic ($\gamma = 1.7$).

currents distribution and therefore can not be predicted a priori nor estimated using a simple expression. Further work on this issue is in preparation. On the contrary, if the electrons are more relativistic, the energy gain per scattering is much larger and the hard tail becomes efficiently populated after just a few scatterings. Therefore, independently on the details of the cross section, in this case we do expect the formation of a spectral tail unbroken, even up to > 1000 keV (see Fig. 5).

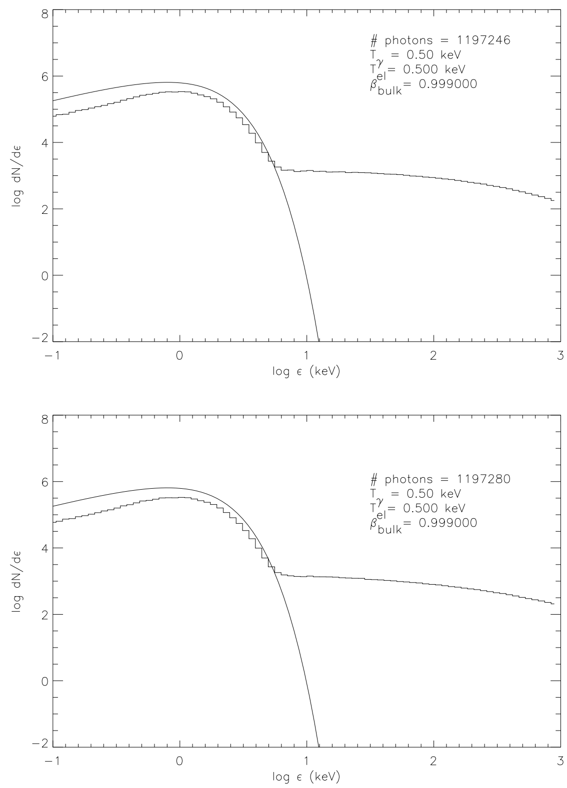

Fig. 5. Same as in Fig.5, but for highly relativistic electrons with $\gamma = 22$.

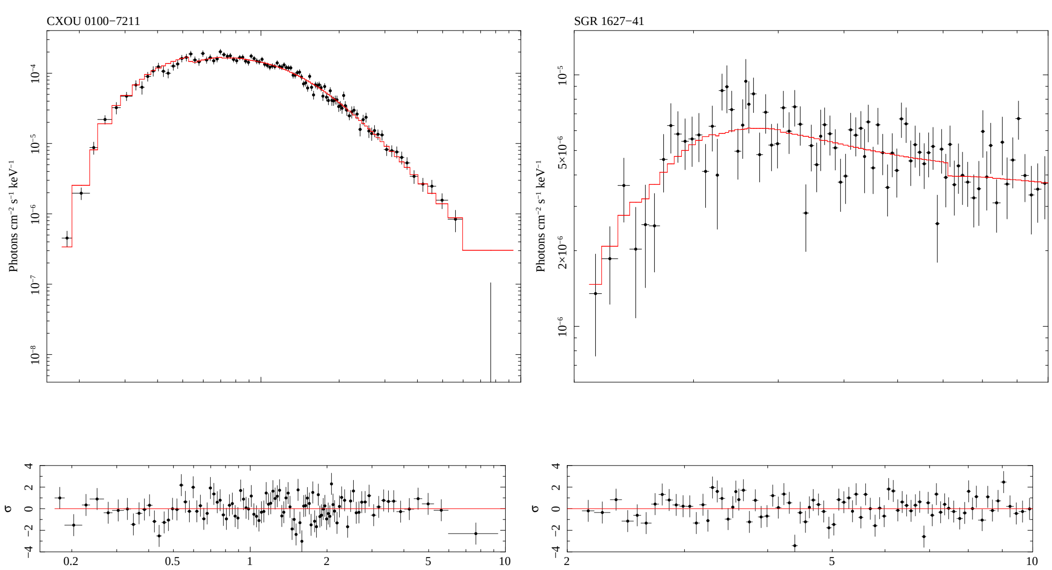

Fig. 6. Fit of the *XMM-Newton* spectra of CXOU J0100-7211 and SGR 1627-41 with the NTZ model. The fitting has been restricted to the $1-10$ keV range (figure re-adapted from Zane, Rea, Turolla & Nobili, 2009, see details therein).

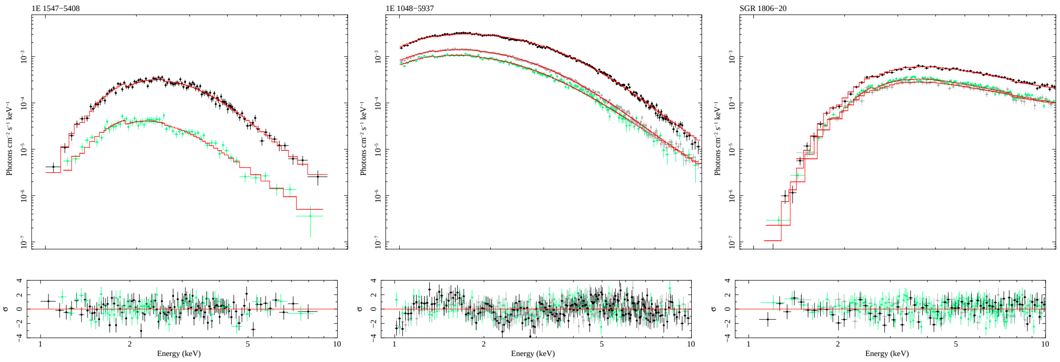

Fig. 7. Same as in Fig. 6 for the AXPs 1E 1547.0-5408 , 1E 1048-5937 and for SGR 1806-20 . In the case of these sources, we performed a joint fit of spectra taken at three different epochs (figure re-adapted from Zane, Rea, Turolla & Nobili, 2009, see details therein).

5 Fitting magnetars spectra in the soft X-ray range

Our non-relativistic code has been used to produce an archive of spectral models that have been subsequently implemented in XSPEC (NTZ model). No attempt is made to fit the value of the polar field strength, that has been fixed at 10^{14} G, and, in order to miminise the number of free parameters, the models in the archive were computed by assuming that the electron temperature is related to β_{bulk} via equipartition (see Nobili, Turolla & Zane, 2008a, for details). We recently applied this model to a large sample of magnetars spectra taken in quiescence. We also considered magnetars that exhibit long-term spectral variation, in which cases we considered a set of two-three observations for each source, corresponding to different spectral states, and performed a joint fit by assuming that only the value of the interstellar absorption remains fixed. A few examples are shown in Figs.6,7 and, for all details and best fit parameters, we refer the reader to Zane, Rea, Turolla & Nobili (2009). Our main result is that, when we restrict to the 1-10 keV band (by using *XMM-Newton* data) the NTZ model successfully reproduces the soft X-ray part of the spectrum of most of the sources (apart from 1E 2259+586 and 4U 0142+614 , which are discussed separately in Zane, Rea, Turolla & Nobili (2009)), as well as the long term spectral variation observed in a few sources, without the need of additional components. This represents a substantial improvement with respect to previous attempts to model magnetars quiescent emission in the same energy band with a simpler 1-D RCS model (Rea et al., 2008), where it was found that in a few cases a PL component was required, in addition to the RCS one, to provide an acceptable fit to the data below 10 keV. We also fitted the combined *XMM-Newton* and *INTEGRAL* spectra of sources with NTZ+PL model, to investigate whether a NTZ model can account for the soft X-ray component in the full spectral energy distribution. Since our XSPEC model is restricted to Thomson limit, for self-consistency it has been artificially truncated at 10 keV and the additional PL is required to simulate the

observed hard tail. Also in this case, we have been able to find a successful fit. However, the fit converges with a hard X-ray component that gives a substantial contribution when extrapolated to the soft X-ray band and, consequently, the best fitting parameters of the NTZ model are substantially different from those we found fitting the 1-10 keV emission only. Whether it is possible that the extrapolation of our spectrum into the hard X-ray domain, when computed by self-consistently accounting for QED effects, is responsible also for the observed *INTEGRAL* tail is matter of future investigations.

6 Conclusions

Results presented here probe that the twisted magnetosphere model, within the magnetar scenario, is in general agreement with observations. As discussed, our 3-D model of resonant scattering of thermal, surface photons reproduces several AXPs and SGRs spectra below 10 keV with no need of extra components. Simulated spectra computed accounting for the whole QED cross sections show that, if magnetospheric electrons are mildly relativistic, a spectral break appears at higher energies. The energy of the spectral break, however, is strongly dependent on the model details.

Our simulations are based on a number of assumptions, among which is the fact that the magnetic field is a simple twisted dipole. We recently investigated the solution for twisted fields with more general force-free configurations, including multipolar component (see Pavan et al., 2000) which allow us to simulate scenarios in which the twist is localized. Nevertheless, we caveat that, at the present status of art, is the physical structure of the magnetosphere which is still an open problem. All our fits require mildly relativistic electrons ($\gamma \sim 1$), therefore the resonant scattering model works well provided that a braking mechanism exists to maintain electrons in a non-relativistic regime (see Nobili, 2009, this issue).

Further works aimed at testing the RCS emission scenario against the variability that is shown during the outbursts of some transient AXPs are in preparation (Albano et al., in prep., Bernardini et al., in prep., Israel et al., in prep.). Also, we plan to use our QED code to study spectral formation and polarization pattern up to ~ 200 keV and to investigate the emission mechanism responsible for the hard X-ray tails detected by *INTEGRAL* (photon upscattering, curvature radiation from particles in the external magnetosphere, or other mechanisms). These results will be presented in forthcoming papers.

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